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Absolute properties of the binary system BB Pegasi

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ABSTRACT

We present a ground based photometry of the low-temperature contact binary BB Peg. We collected all times of mid-eclipses available in literature and combined them with those obtained in this study. Analyses of the data indicate a period increase of $3.0(1)\times10^{-8}$ days/yr. This period increase of BB Peg can be interpreted in terms of the mass transfer 2.4×10^{-8} $M_\odot$ yr^{-1} from the less massive to the more massive component. The physical parameters have been determined as $M_{\rm c}$ = 1.42 $M_\odot$, $M_{\rm h}$ = 0.53 $M_\odot$, $R_{\rm c}$ = 1.29 $R_\odot$, $R_{\rm h}$ = 0.83 $R_\odot$, $L_{\rm c}$ = 1.86 $L_\odot$, and $L_{\rm h}$ = 0.94 $L_\odot$ through simultaneous solution of light and of the radial velocity curves. The orbital parameters of the third body, that orbits the contact system in an eccentric orbit, were obtained from the period variation analysis. The system is compared to the similar binaries in the Hertzsprung-Russell and Mass-Radius diagram.

Subject headings: Binaries:close — binaries: eclipsing — stars: late-type — stars: individual(BB Peg)

1. Introduction

BB Peg (HIP 110493, V = $11^{\rm m}.6$, F8V) is a low-temperature contact binary (LTCB) system which was discovered as a variable star in 1931 by Hoffmeister. Whitney (1959) refined the orbital period. Since then BB Peg has been the subject of several investigations.

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The system was observed photoelectrically in 1978 by Cerruti-Sola & Scaltriti (1980), Zhai & Zhang (1979), and Awadalla (1988). The times of minima of the system have been published by numerous authors.

Cerruti Sola, Milano & Scaltriti (1981) analyzed the BV light curves of Cerruti-Sola & Scaltriti (1980) using the Wilson-Deviney (Wilson & Devinney, 1971; Wilson, 1979; hereafter WD) code. Giuricin, Mardirossian & Mezzetti (1981) solved the same light curves using the Wood (1972) model and obtained somewhat different results. Leung, Zhai & Zhang (1985) used WD to analyze the BV light curves obtained by Zhai & Zhang (1979). Awadala (1988) observed UBV light curves but did not perform a light curve analysis. The mass ratio was determined photometrically for these light curve solutions. The first radial velocity study of the system done by Hrivnak (1990) gives the mass ratio as 0.34(2). More recent radial velocity data obtained by Lu & Rucinski (1999) result in a mass ratio of 0.360(6). The photometric mass ratio (0.360$\mp$0.003) derived by Leung, Zhai & Zhang (1985) agrees very well with the spectroscopic value, a result of the total/annular nature of the eclipses (see Terrell & Wilson, 2005). Zola et al. (2003) published the physical parameters of the components. The orbital period variation was studied by Cerruti-Sola & Scaltriti (1980) and Qian (2001).

2. Observations

The photometric observations of the system were obtained with the 0.4-m (T40), 0.35-m (T35) and 0.30-m telescopes (T30) at the Ege University Observatory (EUO) and TÜBİTAK National Observatory (TUG) on 8 nights during the observing season between August–December 2004 with T35 and 2 nights in 2006 with T40. However, the system was observed at T30 and T40 for only three night in order to obtain the minima times. The light curve of the system was obtained from CCD photometry observations. Light curves of BB Peg in Bessel V and R filters are shown in Fig. 2d and the data are given in Table1. The comparison and check stars were BD+15°4634 and GSC 01682–01530, respectively.

We obtained two minima times throughout these observations. They are listed in Table 2 together with those published in existing literature. Using these minima times we derived the linear ephemeris:

$$HJD\,MinI = 24\,50657.4599(4) + 0.3615015(1) \times E \tag{1}$$

and used them in the reduction processes of the observed data.

3. Eclipse timings and period study

The period variation study of the system was presented for the first time by Cerruti-Sola & Scaltriti (1980), resulting in the ephemeris Min I (HJD) = 2443764.3334(6) + $0.3615021(2)E + 2.3 \times 10^{-11} E^2$. Qian (2001) presented it as Min I (HJD)= 2430285.7618(6)+ $0.36150027(1)E + 2.35(1) \times 10^{-11} E^2$.

Recently, the existence of a third body was reported via spectroscopic study by D'Angelo et al.(2006). We used the linear ephemeris given by Qian (2001) to construct the binary's O-C diagram. It shows almost a sine-like variation superposed on an upward parabola. A sine-like variation in the O-C curve, where both the primary and the secondary minima follows the same trend, suggests the light time effect via the presence of a tertiary component. Times of minima of BB Peg yielded the following equation

$$MinI = T_o + P_o E + \frac{1}{2}\frac{dP}{dE}E^2 + \frac{a_{12}\sin i'}{c}\left[\frac{1-e'^2}{1+e'\cos v'}\sin(v'+\omega') + e'\sin\omega'\right] \qquad (2)$$

where $T_{\rm o}$ is the starting epoch for the primary minimum, E is the integer eclipse cycle number, $P_{\rm o}$ is the orbital period of the eclipsing binary a_{12}, i' , e', and ω' are the semi-major axis, inclination, eccentricity, and the longitude of the periastron of eclipsing pair about the third body, and v' denotes the true anomaly of the position of the center of mass. Time of periastron passage T' and orbital period P' are the unknown parameters in Eq.(2).

Light elements in Eq.(2) were determined using the differential correction method. We used Eq.(2) along with the values given in Table 2 and a weighted least squares solution to derive the parameters shown in Table 3. We assigned weight 10 to photoelectric (pe), 1 to photographic (pg) and 0 (pg) to a few cases that shows high deviation from the expected normal position (the open circles in Fig 1b). The parameters given in Table 3 were used for the $\triangle T_{\rm I}$ variation study of the system which is plotted in Fig 1a. The O-C values in this figure were obtained with the linear elements $T_{\rm o}$ and $P_{\rm o}$ given in Table 3. The line in Fig. 1a shows the secular increase of the binary's orbital period while the dashed line is for both the secular increase and the light-time effect of the tertiary component. We also present the contribution of the light-time effect, $\triangle T_{\rm II}$, to total period variations of the system in Fig 1b. In the last section of this study we will discuss the tertiary component in BB Peg.

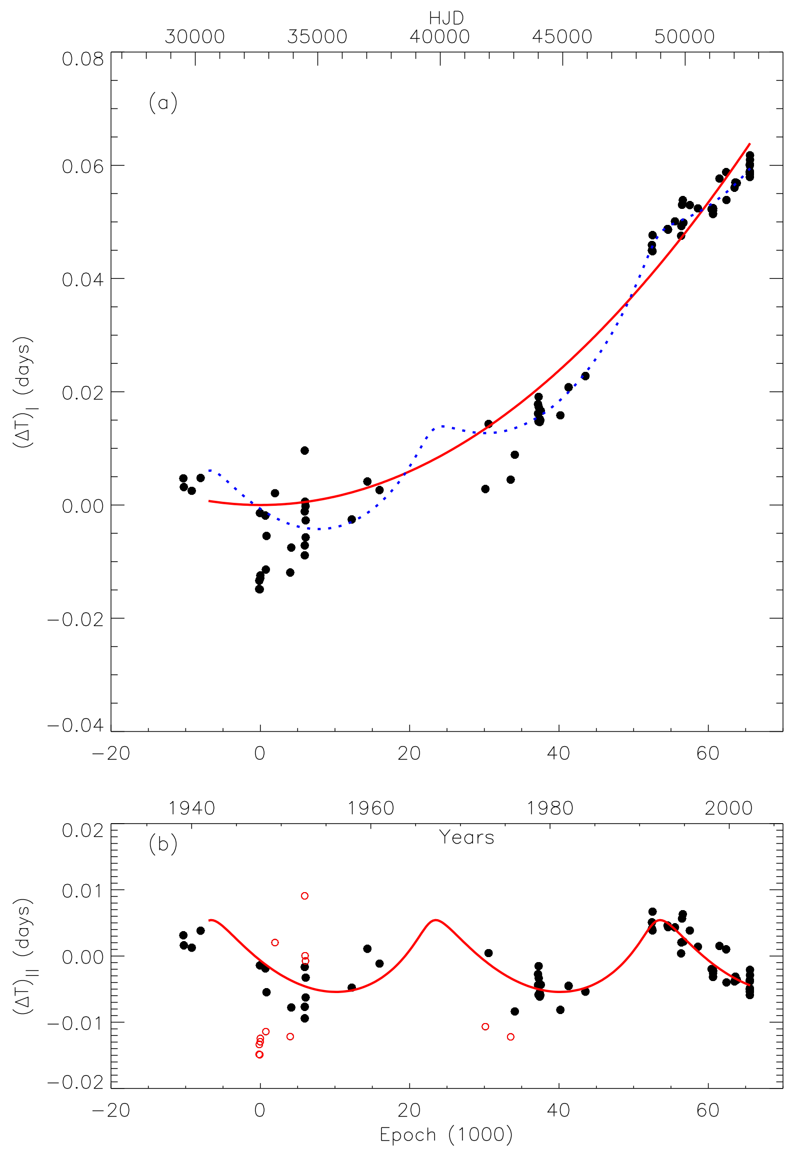

Fig. 1.— (a) The $\triangle T_I$ diagram of the times of mid-eclipses for BB Peg. The continuous line is for the parabolic variation and the dashed line is for a parabolic variation superimposed on the variation due to the tertiary component, (b) the $\triangle T_{II}$ residuals after subtraction of parabolic change, shown in panel (a).

4. Light curve analysis

Previous light curves have been analyzed by either old methods or with the assumption that photometric mass ratio was known. All previously published light curves, as well as those of the current study, have been analyzed simultaneously with the Lu and Rucinski (1999) radial velocities using the latest version of the WD code (Wilson & Devinney 1971; Wilson 1994). Mode 3 of the WD code has used throughout the analysis. As seen in the Fig 2, the light curves show asymmetries in the maxima. Generally it is accepted that the stellar activity may cause to these asymmetries in the light curves, we will discuss these asymmetries in section 5. Hence, the stellar spot parameters, were taken into consideration in our analysis. The adopted values are: $T_1 = 6250\,\mathrm{K}$ according to the $B-V$ color index, gravity darkening coefficients, and albedos were chosen as $g_1 = g_2 = 0.32$ (Lucy 1967) and $A_1 = A_2 = 0.5$ (Rucinski 1969) and the logarithmic limb-darkening coefficients (x_1, x_2) were obtained from van Hamme (1993). Semi major axis of the relative orbit a, binary center-of-mass radial velocity V_γ, inclination i, temperature of the secondary component T_2, luminosities of the primary component L_1(U, B, V, R), the potential of the common surface Ω, and spot parameters (latitude, longitude, size and temperature factor) were adjustable parameters. The results are given in Table 4. Weights for the different sets of data were determined by the scatter of the observations. In all analyses, the B, V and R filters were given 2 times higher weight than the U filter to take their much better dispersion into account. The computed light curves (solid lines) obtained along with the parameters given in Table 4 were compared with all observed light curves shown in Fig. 2a, b, c, and d. The synthetic light curves were created with the LC program.

The obtained parameters for the light curves are given in Table 4 . The results of the different light curve solution models (M) have been denoted by different numbers. It has been assigned M1 in Table 4 to two colors (B and V), light curves solution obtained from Cerruti-Sola & Scaltriti (1980), M2 to two colors (B and V) light curves model of Zhai & Zhang (1979) (the mean values are taken from Leung et al. 1985), M3 to three colors (U, B, and V) light curves that were obtained by Awadalla (1988) and, M4 to two color (R and V) light curves obtained in this study. All the results appear to be compatible with each other. Consistency of observations, using the results given in Table 4, with applied models are shown in Fig. 2a, b, c, and d.

Keeping in mind the possibility of a tertiary component orbiting a third-body orbiting the binary system we assume the 3$^{\rm rd}$ body's (l_3) parameter as a free parameter through the light curve solution. However, we couldn't find meaningful values for the l_3 parameter throughout the solutions. Likewise, D'Angelo et al. (2006) showed that the light contribution of the third body is tiny ($l_3/l_{1+2} = 0.009$).

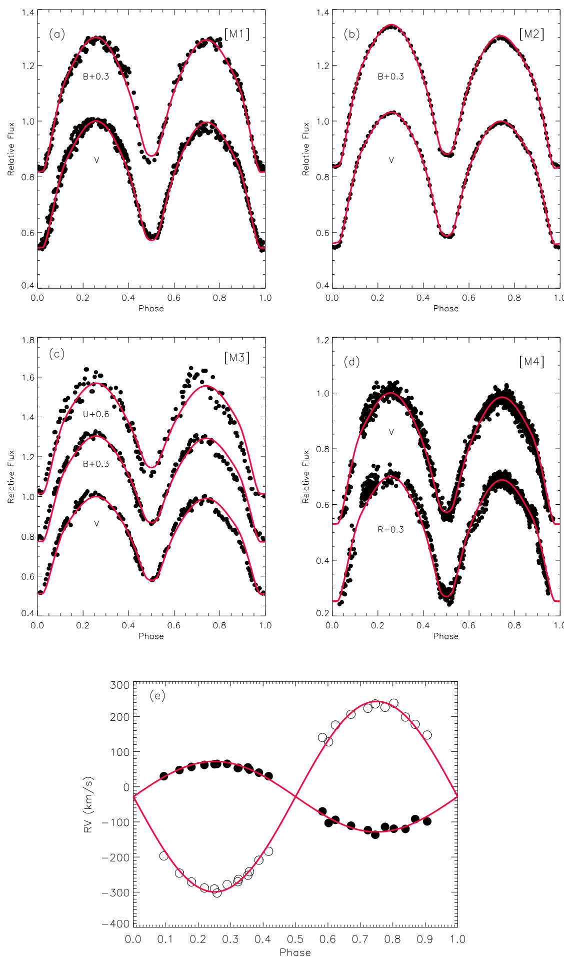

Fig. 2.— The observed and computed light curves of BB Peg. For the sake of comparison the light curves in U, B, and R bands are shifted by a value of +0.6, +0.3, and −0.3 in intensity. Radial velocities (e) from Lu & Rucinski (1999) and the computed curve through our simultaneous solution. See text for the details.

5. Results and Discussion

All available light curves in literature, have been solved using the recent WD code and the results are presented in Table 4. The solutions yielded very close results to each other. During the process effective temperature and absolute magnitude of the Sun were taken as 5780 K and 4.75 mag, respectively. In Fig. 3 the components parameters are shown on the H-R and M-R diagrams. We show them along with the LTCB systems (Yakut & Eggleton 2005) whose physical parameters are well-known. The results obtained from analyzing BB Peg (Table 5) seem to be in good agreement with the well-known LTCBs. Location of the less massive component in the system indicates the system is overluminous and oversized, like the other W-subtype secondary stars. Companion stars appear to be below the ZAMS and the massive component is situated near the TAMS. If interstellar absorption is not taken into account then through the parameters given and using the values given in Table 5 the distance of the system can be found as 361(25) pc. This is consistent with the HIPPARCOS value (ESA 1997). The system's distance is derived from the Rucinski & Duerbeck (1997) in period-color-luminosity relation 389 pc, which is close to the one obtained in this study.

Many contact binaries show an asymmetry in which one maximum is higher than the other (the O'Connell effect), these asymmetries are usually attributed to spots, which we interpret here in a very general sense: they might be due to large cool star spots, to hot regions such as faculae, to gas streams and their impact on the companion star, or to some inhomogeneities not yet understood (Yakut & Eggleton). While the asymmetry is apparent in the shape of the light curve of some systems (e.g. YZ Phe, Samec & Terrell 1995),), in others this asymmetry may not so prominent. (e.g, XY Leo, Yakut et al. 2003). The asymmetry in the light curve of BB Peg is modeled with a cold spot on the secondary component (the cooler with higher mass and radius) of the system. In the model of the light curve denoted by M2 the spot activity appears to be prominent with respect to the other models. The results of the model are summarized in Table 4. Besides, the asymmetry in the light curve is well represented with the model (see Fig. 2).

Fig. 1 shows a parabolic variation. Therefore, we have applied a parabolic fit, and assume that the mass transfer take place between the components. The parabolic ($\triangle T_I$) curve shown in Fig. 1 indicates the existence of mass transfer in the contact system, BB Peg. Upward parabolic variation suggesting a mass transfer from the less massive component (the hotter component in the case of BB Peg) to the more massive one. Eq. (2) yields a period increase at a rate of $\frac{dP}{dt} = 3.0(1) \times 10^{-8}$ days yr^{-1}. If the period increase is indeed caused by conservative mass transfer, then one can estimate the mass transfer between the components. Using the derived masses, we derive the rate of mass transfer $2.4(4) \times 10^{-8}$ M$_\odot$ yr^{-1} from the less massive to the more massive component as in the conservative mass transfer

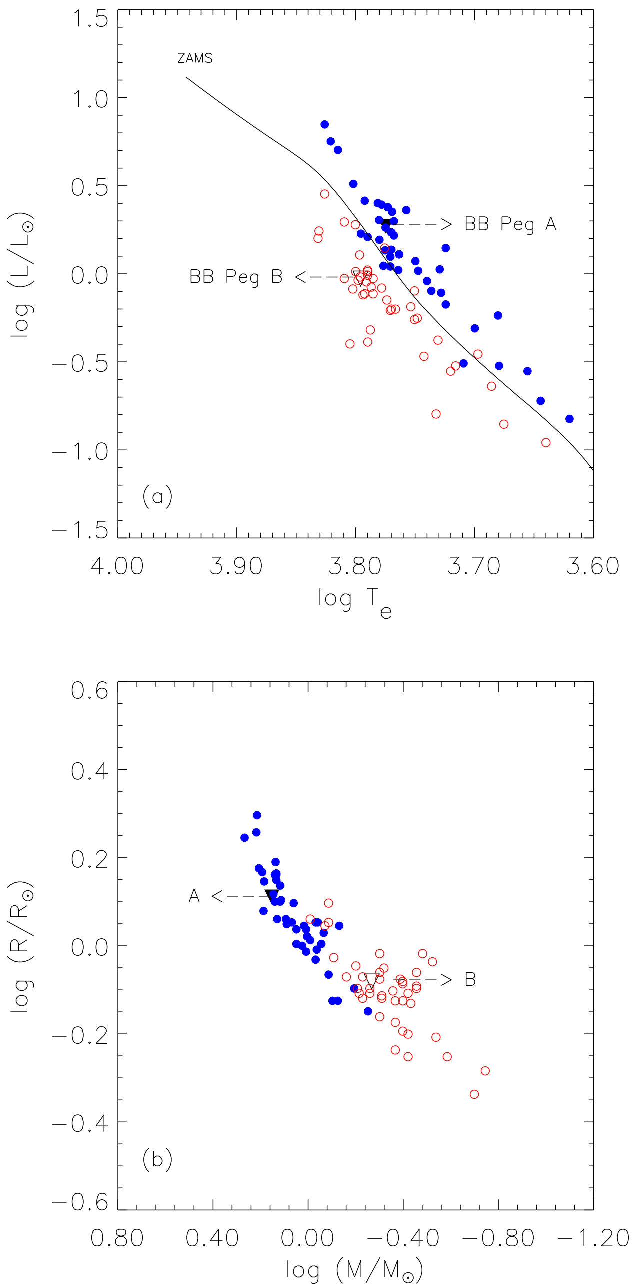

Fig. 3.— The H-R and M-R diagrams showing BB Peg. The filled circles show the primary component of W-type LTCBs, and the open circles are for the secondaries. The ZAMS line is taken from Pols et al. (1995).

approximation. However, conservative mass transfer is just an optimistic assumption. The non-conservative case is very important in close binary evolution (see for details, Yakut & Eggleton and references therein). Analysis of the data, obtained over approximately 25 years, using the WD program indicate a period increase of $2.9(1) \times 10^{-8}$ days/yr, which is close to the one obtained with O-C analysis.

Fig. 1b shows the variation of $\triangle T_{II}$ when the observations extracted from the parabolic variation. The $\triangle T_{II}$ variations show a sine-like variation, which implies the existence of a tertiary component orbiting BB Peg on an eccentric orbit. Spectroscopic study of the system shows the existence of an M -type dwarf star about the binary (D'Angelo et al. 2006). Using this information with sine-line variation of the residuals of (O-C) we solved the system under the assumption of existence of a third body and obtained the values given in Table 3. The results of the (O-C) analysis show that the third component has a highly eccentric orbit (e = 0.56) with about a 30-year period. Indeed, (O-C) residuals may indicate that the source of this variation could be due to magnetic activity. The orbit of third body, obtained in this study compared to the data of Pribula & Rucinski (2006) appeared to be much more eccentric.

On the other hand, using the values given in Table 3 and Table 5 one may predict the mass of the tertiary component. By assigning 0.96 AU to $a_{12}\sin i$ and 29.7 yr to period one can give the mass function as $0.0010\,M_{\odot}$. For orbital inclinations (i_3) of 90, 80, 50, 30, 10 the masses of the third body (m_3) are estimated to be 0.161, 0.164, 0.214, 0.341, 1.229 $\mathrm{M}_{\odot}$, respectively. D'Angelo et al. (2006) found a temperature of 3900 K for the tertiary component and a luminosity ratio ($\beta = \frac{l_3}{l_1+l_2}$) of 0.009. Following this information with the deduced luminosities given in this study one may give the radius of third body as 0.33 $\mathrm{R}_{\odot}$. $M \simeq 0.978R$ relationship is deduced using the ten well-known M-type dwarf stars given in the study of Mercedes & Ribas (2005), then the tertiary body's mass of 0.32 $\mathrm{M}_{\odot}$ is found. Taking into consideration that value of mass, the orbital inclination of the third body can be found as 35°. Useful observations of BB Peg throughout the next decade will help to determine the accurate orbital parameters of the third body from the O–C diagram.

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Table 1: VR measurements of BB Peg (Fig. 2d). The phases were calculated using the Eq. (1). 1 and 2 denote V, and R filters (F), respectively.

HJD	Phase	Δm	F
53301.3054	0.5115	1.2930	1
53301.3067	0.5151	1.2840	1
53301.3080	0.5187	1.2610	1
53301.3093	0.5224	1.2500	1
53301.3106	0.5260	1.2300	1
53301.3119	0.5296	1.2050	1
53301.3133	0.5333	1.1840	1
53301.3146	0.5369	1.1690	1
53301.3159	0.5405	1.1560	1

Note. — Table 1 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

Table 2: The primary (I) and the secondary (II) minima times in HJD*(HJD - 2 400 000).

HJD*	Min.	Ref.	HJD*	Min.	Ref.	HJD*	Min.	Ref.
26559.241	II	1	41181.397	I	5	50657.4575	I	16
26582.014	II	2	41335.227	II	6	50671.3770	II	16
26965.204	II	2	42405.259	II	7	50702.4698	II	17
27393.223	II	2	42607.523	I	8	50739.7052	II	18
30226.826	I	3	42748.310	II	8	50769.525	I	18
30235.865	I	3	43729.4491	II	9	51078.4304	II	19
30258.638	I	3	43730.3512	I	9	51471.3810	II	20
30264.797	I	3	43754.3896	II	9	52131.8425	II	21
30281.776	I	3	43754.3896	I	9	52201.2508	II	22
30285.753	I	3	43757.4667	I	9	52201.4305	I	22
30530.861	I	3	43764.3334	I	9	52203.2386	I	22
30552.903	I	3	43806.08453	II	10	52203.4188	II	22
30584.721	I	3	43806.98838	I	10	52207.3962	II	22
30994.128	II	2	43813.13365	I	10	52513.4118	I	23
31731.756	I	4	43814.03710	II	10	52838.402	I	24
31783.455	I	4	43842.05373	I	10	52852.4956	I	25
32433.631	II	4	43866.99893	I	10	53243.4607	II	26
32433.801	I	4	44812.503	II	11	53284.3112	II	22
32436.687	I	4	45208.3511	II	12	53285.3957	II	22
32436.866	II	4	45208.5319	I	12	53353.3577	II	26
32451.697	II	4	46024.2600	II	12	53984.3589	I	26
32455.683	II	4	46026.2483	I	12	53984.3591	I	26
32473.567	I	4	49243.4462	II	13	53984.5409	II	26
32477.538	I	4	49244.3490	I	13	53984.5411	II	26
32477.744	II	4	49273.2689	I	13	53986.5271	I	26
32479.710	I	4	49275.2600	II	13	53986.5276	I	26
34711.615	I	4	50001.3351	I	14	53992.4949	II	26
35468.604	I	4	50026.2785	I	14	53992.4957	II	26
36056.764	I	4	50359.4028	II	15			

References for Table 2. (1) Zessewitsch (1939), (2) Tsessevich (1954), (3) Whitney (1943), (4) Whitney (1959), (5) Diethelm (1973), (6) Locher (1973), (7) Diethelm (1976), (8) Diethelm (1977), (9) Cerruti-Sola & Scaltriti (1980), (10) Zhai & Zhang (1979), (11) Derman et al. (1982), (12) Awadalla (1988), (13) Müyesseroğlu et al. (1996), (14) Agerer & Hübscher (1996), (15) Agerer & Hübscher (1998a), (16) Ogloza (1997), (17) Agerer & Hübscher (1998b), (18) Samolyk (1999), (19) Agerer et al. (1999), (20) Agerer et al. (2001), (21) Nelson (2002), (22) Drozdz & Ogloza (2005a), (23) Demircan et al. (2003), (24) Bakış et al. (2003), (25) Hübscher (2005), (26) Present study.

Table 3: Orbital elements of the tertiary component in BB Peg. The standard errors 1σ, in the last digit are given in parentheses.

Parameter	Unit	Value
T_o	[HJD]	2430285.7655(36)
P_o	[day]	0.3615006 (1)
P'	[year]	27.9(2.0)
T'	[HJD]	2438540 (793)
e'		0.56 (0.30)
ω'	[°]	69 (18)
$a_{12} \sin i'$	[AU]	0.96 (15)
$f(m)$	[$M_\odot$]	0.0010(5)
$m_{3;i'=10^\circ}$	[$M_\odot$]	1.23
$m_{3;i'=90^\circ}$	[$M_\odot$]	0.16
Q	[c/d]	$1.5(2) \times 10^{-11}$

Table 4: The photometric elements of BB Peg with their formal 1σ errors. See text for details.

Parameter	M 1	M 2	M 3	M 4
Geometric parameters:				
i (°)	85.3(6)	87.9(1.4)	84.6(9)	85.0(5)
V_γ	-27.8(1.7)	-	-28.0(2.0)	-28.1(2.2)
a	2.665(30)	-	2.671(30)	2.664(32)
$\Omega_{1,2}$	6.066(14)	6.045(6)	6.005(20)	6.056(13)
q	2.752(27)	-	2.690(34)	2.702(7)
Filling factor (%)	35	38	33	34
Fractional radii of h. c.				
$r_{1\ pole}$	0.2898(12)	0.2888(4)	0.2922(15)	0.2889(19)
$r_{1\ side}$	0.3042(14)	0.3028(5)	0.3068(19)	0.3030(24)
$r_{1\ back}$	0.3490(27)	0.3450(10)	0.3522(34)	0.3457(45)
Fractional radii of c. c.				
$r_{2\ pole}$	0.4541(11)	0.4499(4)	0.4529(14)	0.4507(16)
$r_{2\ side}$	0.4894(15)	0.4839(5)	0.4881(19)	0.4849(22)
$r_{2\ back}$	0.5209(20)	0.5145(7)	0.5200(25)	0.5157(30)
Radiative parameters:				
$T_1{}^*$ (K)	6250	6250	6250	6250
T_2 (K)	5905(45)	5945(40)	5760(45)	5955(30)
Albedo* ($A_1 = A_2$)	0.5	0.5	0.5	0.5
Gravity brightening* ($g_1 = g_2$)	0.32	0.32	0.32	0.32
Luminosity ratio: $\frac{L_1}{L_1+L_2}$ (%)				
U	-	-	45	-
B	37	36	41	-
V	36	34	38	34
R	-	-	-	32
Spot parameters:				
Colatitude	1.24(7)	1.52(3)	1.20(15)	1.05(16)
Longitude	4.18(27)	4.36(6)	4.26(40)	4.78(29)
Spot radius	0.18(2)	0.34(2)	0.24(3)	0.25(2)
Spot temperature	0.92(2)	0.89(1)	0.93(2)	0.92(2)

* Fixed

Table 5: Absolute parameters of BB Peg. The standard errors 1σ in the last digit are given in parentheses.

Parameter (Unit)	Hot component	Cool component
Mass ($M_\odot$)	0.53 (2)	1.42 (4)
Radius ($R_\odot$)	0.83 (2)	1.29 (2)
Effective temperature (K)	6250	5950 (30)
Luminosity ($L_\odot$)	0.94 (6)	1.86 (8)
Surface gravity (cgs)	4.33	4.37
Absolute bolometric magnitude (mag)	$4.82^{-0.08}_{+0.09}$	$4.08^{-0.13}_{+0.08}$
Absolute visual magnitude (mag)	4.98	4.26
Distance (pc)	361^{-25}_{+20}	